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ABSTRACT

HELIOS-1 moved from 1 AU on December 10, 1974, to 0.31 AU on March 15, 1975, and the sun rotated beneath the spacecraft nearly four times during the interval. Recurrent high-speed streams with uniform magnetic polarity were observed, and they were associated with coronal holes of the same polarity. Although recurrent, the streams and their magnetic field patterns were not stationary, because the coronal holes which produced them changed in shape and latitude from one rotation to the next. We estimated that the magnetic field intensity of open field lines in some of these holes was on the order of 10 to 20 gauss. Recurrent slow flows were also observed. The magnetic field polarity and intensity in these flows were irregular and they changed from one rotation to the next.

Cold magnetic enhancements (CME's) characterized by a 2 to 3 fold enhancement of magnetic field intensity and a 5 to 7 fold depression of proton temperature relative to conditions ahead of the CME's, were observed in some slow flows. Some of these CME's were contiguous with interaction regions of streams.

At perihelion, HELIOS observed a recurrent stream which was associated with a lobe of the south polar coronal hole. The longitudinal width of the stream was three times that of the hole. We estimate that the width of the eastern and western boundaries of the streams at the coronal holes was only $2.5^{\circ} \pm 1.5^{\circ}$, and we infer that the width at the northern boundary of the stream was $\leqslant 5^{\circ}$. We conclude that between the sun and 0.3 AU there was a diverging stream surrounded by a thin boundary layer in which

there was a large velocity shear. There is evidence for compression of the magnetic field in the western boundary layer (interaction region), presumably due to steepening of the stream within 0.31 AU. The magnetic field must be considered in models of the boundary layer and the stream.

I. INTRODUCTION

The principal purpose of this paper is to describe and interpret the flow-related interplanetary magnetic field patterns observed by HELIOS-1 as it moved from 1 AU on December 10, 1974 to 0.31 AU on March 15, 1975, and back to 0.54 AU on April 7. The radial position of the spacecraft is shown in the bottom panel of Figure 1. The solar longitude of the spacecraft, measured in units of 360° and counted from the longitude at launch, is shown in the top of panel of Figure 1. The sun rotated beneath the spacecraft nearly four times in the interval to be discussed.

The magnetic field data presented below are from the Rome/GSFC magnetometer, which is described by Scearce et al. (1975) and by Mariani et al. (1977). In order to understand the magnetic field patterns, one must consider them in relation to the plasma, for the magnetic field and plasma are strongly coupled because of the very high electrical conductivity of the plasma. The plasma data presented below were obtained by the instrument of Rosenbauer et al. (1977) on HELIOS-A. Hourly averages of the proton speed, density, and temperature will be discussed insofar as they are relevant to understanding the magnetic field observations.

Section II describes the recurrent flow and field patterns observed by HELIOS and the relation between these patterns and coronal holes. Four types of recurrent patterns were observed: a large recurrent stream, a recurrent slow ("quiet") flow, a rapidly evolving flow, and a recurrent compound stream. It is shown that the recurrent streams were not stationary, for although the sources recurred at approximately the same longitudes on

successive rotations, the shapes and latitudinal patterns changed appreciably from one rotation to the next.

A new type of magnetic field and plasma structure characterized by a low ion temperature and a high magnetic field intensity is discussed in Section IV. We call this a cold magnetic enhancement, CME. Its nature, structure, and relation to streams are described in this section.

The structure of stream boundaries between the sun and $\approx$ 0.3 AU is discussed in Section IV. We show that near the sun interaction regions can be narrower and streams can be steeper than at 1 AU. It is shown that recurrent streams can have sharp boundaries in both latitude and longitude between the sun and 0.3 AU, with large velocity shears across these boundaries. The evolution of streams in this case is very different from that described by the recurrent stream models in the literature.

The structure of the boundaries of streams between 0.3 AU and 1 AU has been studied by Schwenn et al. (1977) and by Rosenbauer et al. (1978), who concluded that the boundaries are thin at 0.3 AU. The present results suggest that the boundaries are narrow because the flows originate in coronal holes which themselves have sharp boundaries. Indirect evidence for sharp boundaries near the sun has been found in observations of the solar wind at 1 AU. Considering the trailing part of recurrent streams, Lazarus (1975) and Nolte and Roelof (1977) inferred that the width of the trailing edges of streams in the high corona is $\approx 4^{\circ}$ to 6°, assuming that the solar wind speed is effectively constant between the corona and 1 AU. Gosling et al. (1977) suggested that stream interfaces at the leading edges of streams at 1 AU (Belcher and Davis, 1971;

Burlaga, 1974; Burlaga *et al.*, 1971) are the result of a discontinuous longitudinal shear boundary near the sun.

II. RECURRENT MAGNETIC FIELD AND FLOW PATTERNS AND THEIR RELATIONS TO CORONAL HOLES

Figure 2 shows the polarity of the magnetic field (+ away from the sun) and the speed of the solar wind versus longitude (in units of 360°) for the four solar rotations during which HELIOS-1 moved from 1 AU at launch to 0.31 AU and back out to 0.54 AU. HSR 0 is the longitude of HELIOS at the time of launch. Four distinct sequences are identified by the vertical lines and Roman numerals in the Figure. In Sequence I a large, unipolar stream recurs with apparently little change during the first three rotations. It was not seen in its entirety on the fourth rotation for reasons which will be discussed in Section IV. In Sequence II, the speeds are relatively low, the polarity is variable, and there are no distinct streams. One might say that this is a recurrent "quiet" solar wind, or more precisely a recurrent slow flow. In Sequence III one sees an evolving pattern in the magnetic polarity and the speed profile. The emergence of a stream is seen on rotation four. Sequence IV consists of a unipolar, compound, recurrent stream which changes in detail from one rotation to the next. The approximate spatial structure of the four sequences is shown in Figure 3.

The magnetic field intensity patterns corresponding to the polarity and speed patterns are shown in Figure 4. Three types of magnetic field enhancements can be seen. The type of enhancement indicated by the shaded areas in Figure 4 occurred in the interaction regions of recurrent streams (interaction regions have been defined by Burlaga and Ogilvie (1970) and Burlaga (1975) as regions in which the speed is increasing and the pressure is high). Such enhancements are seen in the interaction regions

in Sequence I, in Sequence IV on HSR 0 and 1, and in Sequence III on HSR 3. A second type of magnetic field enhancement occurred in the slow flows and was not related to interaction regions. This type is most evident on HSR 0 and HSR 1 in Sequence III and on HSR 1 in Sequence II (see Figure 4). A third type of enhancement, which was produced by a shock wave, occurred on HSR 1.03, corresponding to January 6, hour 20. Enhancements which occur in interaction regions are partly due to the kinematic effect of the steepening of a stream (e.g., see Hundhausen, 1972; Burlaga and Barouch, 1976). Since the enhancements in slow flows are not closely related to velocity gradients, it is likely that they originate near the sun; however, their specific source is unknown at present.

Let us now consider the sources of the streams in Figure 2. In particular, we shall consider the relationship between the streams and coronal holes, since a relationship has been demonstrated for other streams by many authors (Pneuman, 1973; Noci, 1973; Krieger _et al._, 1973; Neupert and Pizzo, 1974; Sheeley _et al._, 1977; Burlaga _et al._, 1977; Hundhausen, 1977). Coronal holes are most clearly seen in high resolution X-ray images of the sun, such as those obtained by Skylab. They can also be seen in XUV images, in ground-based observations of the K-coronal brightness (Hansen _et al._, 1969) and in ground-based observations of the He I 10830Å line (Harvey _et al._, 1975a,b). The white light observations refer to structure at a distance of $\approx 1.1\ R_\odot$ to $1.8\ R_\odot$ from the sun's center, while the He I 10830Å observations refer to structures just above the photosphere. The K-coronometer observations are daily, line-of-sight observations of brightness over the limb. They give a global picture of the coronal holes

over many years, but they are relatively insensitive to small equatorial holes. The He I 10830A observations indicate the location of coronal holes against the solar disk as areas in which the chromospheric network is relatively weak or absent. They give coronal hole boundaries similar to the X-ray and XUV boundaries, with somewhat lower resolution ($\pm5^{\circ}$). Thus the He I 10830A observations and the K-coronometer observations are complementary, the former giving the detailed structure of coronal holes near the chromosphere and the latter given the large-scale structure $\approx$ 1.1 to 2.0 $R_{\odot}$ above the chromosphere.

Schwenn et al. (1977) have shown a relationship between the large-scale stream structure observed during the prime HELIOS-1 mission and the K-coronograph (white-light) observations at that time. In this paper we relate the streams to coronal holes observed in the Kitt Peak He I 10830A images. Figure 5 shows the coronal holes identified during the primary mission of HELIOS-1. The coordinates are solar latitude and solar longitude in Carrington rotations. Longitude is shown decreasing to the right (in contrast to the conventional plot), so that the patterns can be compared directly with the stream patterns in Figure 2. Coronal hole boundaries indicated by the closed solid curves in Figure 5 are considered to be accurate to within 10°. The dashed lines indicate possible coronal hole boundaries, but the identifications are not firm. The solid areas indicate active regions. The solar projection of the trajectories of the earth and the HELIOS spacecraft are shown by the solid curves across each panel; the motion of the earth and the spacecraft is from left to right. Note that on HSR 0 through 2 (CR 1622-1625), HELIOS and Earth have the same solar latitude. On HSR 3 (CR 1625-1626) HELIOS moves 15° northward with

respect to Earth as it goes to the opposite side of the sun, which is inclined 7.5° with respect to the ecliptic plane.

In previous papers, streams were related to coronal holes by projecting the streams to the sun backward in time, assuming that each volume element moves with a constant speed. One can obtain the relative positions of streams and holes without making such a projection. In Figure 2, the front edge of each stream is marked by a vertical line with a label A0, A1, L0 and L3, etc. Note that the speed is approximately 400 km/s in every case. In Figure 4 the front edge of each coronal hole is marked by a vertical arrow, and each arrow is labeled with the symbol of the stream in Figure 2 that we associate with the coronal hole. For example, the front edge of the hole A2 in Figure 5 is associated with the edge of the stream labeled A2 in Figure 2. If our associations are correct, a plot of the longitude of the stream edges seen by HELIOS versus the Carrington longitude of the front edges of the coronal holes should give a smooth curve. Figure 6 shows such a plot, and indeed the points fall near a line. The relative position of the leading edge of the source of any particular stream can be determined from this line within approximately 10°. For example, stream A2 in Figure 2 was observed at HSR 2.23 and Figure 6 implies that its source is at 143° on CR 1624, as observed. The associations made in this way are confirmed by comparing the interplanetary magnetic field polarity with the measured photospheric magnetic field polarity beneath the coronal holes (Table I).

The coronal holes in Figure 5 can be grouped into four sequences corresponding to the flow and polarity sequences in Figure 2. The recurrent streams in Sequence I are related to an extension of the southern polar

coronal hole. The coronal hole observations corresponding to Sequence II are not complete. The evolving flow in Sequence III is related to a coronal hole sequence (G in Figure 5), due to a hole in the southern hemisphere on HSR 1 and holes just north of the equator on HSR 2 and 3. Apparently only edge flows were seen on HSR 1 and 2 whereas a fully developed stream with sharp boundaries was observed on HSR 3; the implications of this are discussed in Section IV. The recurrent compound stream in Sequence IV is related to a recurrent, evolving pair of coronal holes (L and M in Figure 2).

An important feature of the coronal holes in Figure 5 is that although they tend to recur at the same longitude from one rotation to the next there is considerable change in the boundaries of the coronal holes from one rotation to the next. Thus, the coronal holes are recurrent but not stationary. The streams which originate in these holes are likewise recurrent, but may change in detail from one rotation to the next due to the changing shape and latitude of the coronal holes. In other words, the recurrent streams are not stationary, and changes from one rotation to the next can be attributed to changing conditions in the source.

It is possible to estimate the magnetic field intensity in some of the coronal holes which produced streams and fields observed by HELIOS. In particular, if one considers nearly circular, near-equatorial holes, then one can use the method of Burlaga et al. (1977) to calculate the average field in the hole, B_h, given a) the average intensity of the measured interplanetary magnetic field which comes from that hole, $< B_x >$, measured at some distance r_s from the sun, b) the width of the stream, α_s, and c) the longitudinal width of the coronal holes, α_h. If the field lines expand equally in latitude and longitude, if the stream fields are unipolar,

and if the angular extent of the open field lines at the source is the same as that of the coronal hole, then the principle of flux conservation gives

$$B_h = \langle B_s \rangle \left(\frac{r_s}{r_\odot}\right)^2 \left(\frac{\omega_s}{\omega_h}\right)^2 \cos^2 \sigma \qquad (1)$$

where σ is the angle that the spiral magnetic field makes with the radial direction. Equation (1) actually gives an upper limit on B_h, since the divergence of the field lines is generally less than or equal to that assumed in deriving (1), and since the field is generally not unipolar in a stream. The coronal holes which best satisfy the assumptions used in deriving (1) are L0, L1, L2, and G3. The relevant measurements of these holes and the associated magnetic fields are given in Table 2, together with B_h from 1. We conclude that the magnetic field intensities in the holes are on the order of 10 to 20 gauss, consistent with the estimates of Zuriaga et al. (1977) for equatorial holes observed in 1973, 1974.

TABLE 1

COMPARISON OF INTERPLANETARY AND SOLAR POLARITIES

Stream	Solar Polarity	IP Polarity
A0	-	-
A1	-	-
A2	-	-
A3	-	-
L0	+	+
L1	+	+
L2	+	+
L3	+	+
M0	+	+
M1	+	+
M2	+	+
G1	-	(-)
G2	+	(+)
G3	+	+
N0	+	+
E2	+	+
P2	-	+
B3	-	-
C3	+	-

TABLE 2

PROJECTED MAGNETIC FIELDS IN CORONAL HOLES

HOLE	α_h	α_s	$< B_s >$ (γ)	σ	r_s (AU)	B_h (gauss)
L0	13^o	52.0^o	6.2	43.5^o	0.95	21.7
L1	18^o	54.5^o	10.5	37.9^o	0.78	16.8
L2	16^o	39.5^o	22.0	24.2^o	0.45	10.5
G3	17^o	46.4^o	18.4	26.0^o	0.49	12.2

III. COLD, MAGNETIC FIELD ENHANCEMENTS

Figure 7 shows a structure characterized by an enhancement in magnetic field intensity and a depression in temperature lasting 30 hrs, corresponding to a radial extent of 4.6×10^7 km or 0.31 AU. We shall call such structures cold magnetic enhancements (CME's). The CME in Figure 7 occurs just ahead of a recurrent stream, where the solar wind speed is low ($\approx$ 425 km/sec). The magnetic field intensity in the filament is 2.1 times that just ahead of the filament, and the corresponding temperature ratio is 0.2.

Another CME is shown in Figure 8. This was observed by HELIOS at 0.48 AU. The ratio of the magnetic field intensity in the filament to that ahead of it is 2.5. The temperature profile is somewhat complicated, but the temperature does decrease by a factor of $\approx$ 7 in the filament. The filament occurs just ahead of a stream, where the speed is low. It is so close to the interaction region that the magnetic field enhancement appears to be a single structure, but close inspection shows separate maxima corresponding to the CME and the interaction region.

Two additional CME's are shown in Figure 9 (labeled L2 and P2a). The enhancement labeled L2 occurs just ahead of a stream, but the enhancement in B and depression in T are smaller than in the other examples that were discussed. The CME labeled P2a shows a large enhancement in B (approximately a factor of 3) and a very large depression in T_p (approximately a factor of 22). This occurs in the middle of a compound stream, where the speed is $\approx$ 500 km/sec. However, it just precedes a large gradient in V and it is adjacent to a secondary enhancement in B and which occur in the interaction region corresponding to the speed gradient. Thus, it is possible that this CME does not originate in a coronal

hole, but rather comes from a region between the coronal holes that produced the compound stream. This source, determined from Figure 6, is shown by the circled x between M2 and P2 on CR 1625 in Figure 5.

The four CME's described above show that some streams do not move through a nearly uniform, ambient medium, contrary to the assumptions in all current stream models; rather, they are preceded by and interact with cold magnetic enhancements. To determine the quantitative size of these effects, one must model the interaction of a stream with a CME. This will be considered in another paper. The magnetic filaments are, of course, modified by the stream, and again a model is needed to evaluate the quantitative effects. Qualitatively, however, the stream will tend to compress the filament, causing an increase in B, n, and T. If the compression is confined to a region with a dimension of a few tenths of an AU along $\underline{B}$, a mass flow can be driven along $\underline{B}$ which will tend to diminish the density enhancement. Similarly, a heat flux along $\underline{B}$ could reduce the size of any increase in T which might be produced by compression. Thus, the enhancement in B in a CME would be increased by the stream interaction and the size of the temperature depression would tend to be reduced. In this picture, the temperature depression in a CME is likely due to a low temperature at the source of the filament.

The source of CME's presents a problem for which we have no unique solution. One possibility is that a CME is related to the boundary-zone between the edges of a coronal hole and the neutral lines of the "unipolar" magnetic cell in which the hole lies. Such boundary-zones were identified for the Sky-lab period (Bohlin, 1976). The low temperature in a CME might be due to a predominance of closed magnetic field lines in the boundary zone.

If this is the case, the fact that the high field intensity appears in the low temperature region which precedes the stream but not in the low temperature region following the stream suggests that the enhancement is due at least in part to compression by the stream. CME's have three characteristics in common with structures called non-compressive density enhancements (NCDE's; Gosling et al., 1977), viz., 1) their observed durations are similar, 2) the temperature is low in both, and 3) both occur just ahead of fast streams. However, they differ in two respects: 1) the magnetic field intensity is always high in CME's, but it is generally not high in NCDE's (Gosling et al., 1977), and 2) the density is always high in NCDE's, but it is generally not high in CME's. It is possible that CME's and NCDE's are just two subsets of a more general phenomenon, the essential feature of which is a low temperature just ahead of a stream. Both might be due to boundary conditions adjacent to a coronal hole, but Gosling et al. (1977) argued that NCDE's might be transients that have been swept-up by streams.

IV. BOUNDARIES OF STREAMS FROM CORONAL HOLES

HELIOS-1 observed a recurrent stream at 0.3 AU, providing an exceptional opportunity to study the structure of a stream at this distance and its relation to the sun. Observations of the stream and its magnetic field are shown in Figure 10, in the interval labeled A3. Observations of coronal holes at this time are shown at the bottom of Figure 10: the scale and position of the coronal hole map were chosen such that it can be compared directly with the flows shown above it. Schwenn et al. (1977) have already shown that the general location of the stream is related to a broad extension of the southern polar hole as seen with low resolution at $\approx 1.5\ R_\odot$ in K-coronometer observations, and they have demonstrated that the latitudinal boundary of the stream was sharp between 0.3 AU and 1 AU. We shall show that the structure of the stream was related in detail to the structure of the coronal hole seen in He I 10830Å images of the chromosphere and that the latitudinal and longitudinal boundaries of the stream were sharp between the sun and 0.3 AU.

The stream A3 in Figure 10 had a longitudinal extent of only 30°. It was associated with a narrow lobe of the southern polar hole, the longitudinal extent of which was $\approx 10^\circ$. If the width of the stream near the sun was the same as that of the coronal hole, this implies that the flow diverged by a factor of 3 in longitude between the sun and 0.3 AU. This is consistent with the divergence of flow from a polar coronal hole measured directly by Monroe and Jackson (1976), who obtained a divergence factor of ≈ 2.9 between the sun and $5\ R_\odot$. No sector boundary was observed near the stream A3, and the magnetic polarity was uniform for several days preceding and following the stream as well as in the stream itself. This indicates

that the stream and its associated coronal hole were imbedded in a large, "unipolar" magnetic region.

The plasma observations presented in Figure 10 show that the longitudinal boundaries of the stream were very sharp at 0.3 AU. At the front boundary, the speed increased from 345 km/s to 625 km/s over an angle $\delta_H = 2.1^\circ$. Since the velocity and magnetic field were nearly radial, this implies a velocity shear of > 130 km/s/deg. At the rear boundary of the stream the speed decreased from 625 km/s to 345 km/s over an angle of $\delta_{Hz} = 12.3^\circ$, corresponding to a velocity shear of $\gtrsim$ 20 km/s/deg. The fact that the front boundary is thinner than the rear boundary can be attributed to kinematic steepening between the sun and 0.3 AU. This interpretation is supported by the observation that the magnetic field reached a maximum within the forward boundary, which is a natural consequence of the compression that accompanies kinematic steepening. If dynamical effects could be neglected within 0.3 AU, we could project the measured widths of the stream boundaries to some sphere close to the sun (say $r_o = 2.5\ R_\odot$) using the equations for spiral field lines. This gives

$$\delta_o^{\pm} = \delta_H^{\pm} \pm \Omega_s\ (r_H - r_o) \left(\frac{V_f - V_s}{V_f \quad V_s} \right) \qquad (2)$$

where $\Omega_s = 2.8 \times 10^{-6}\ \text{sec}^{-1}$ is the angular rotation rate of the sun and the minus (plus) sign is chosen when discussing a region of increasing (decreasing) speed. Considering the front boundary of the stream A3 observed by HELIOS, where V increased from 345 km/s to 625 km/s over an angle $\delta_H^{+} = 2.1^\circ$, we find that at $\approx 2.5\ R_\odot$, $\delta_o^{+} = 11.8^\circ$. Similarly, considering that part of the trailing boundary of the stream where the

speed decreased from 625 km/s to 345 km/s over an angle $\delta_H^- = 12.3^\circ$ we find that $\delta_o^- = 2.9^\circ$ at $\approx 2.5\ R_\odot$. The inequality between δ_o^+ and δ_o^- suggests that our assumption of constant V and negligible pressure (i.e., the kinematic approximation) is not valid. Nevertheless, δ_o^+ is an upper limit and δ_o^- is a lower limit, so we can conclude that the width of the stream boundaries at $\approx 2.5\ R_\odot$ was $\approx 7.4^\circ \pm 4.5^\circ$. Assuming a longitudinal divergence factor of 3 between the corona and $2.5\ R_\odot$, we find that the longitudinal width of the stream boundary around the coronal hole was only $\approx 2.5^\circ \pm 1.5^\circ$. This is consistent with the width of the coronal hole boundary, which is $\leqslant 10^\circ$.

We can infer that the latitudinal boundary of the stream was also thin between the sun and 0.3 AU, due to a fortunate alignment between the spacecraft trajectory and the northern boundary of the coronal hole. Figure 10 shows that HELIOS moved nearly parallel to the northern boundary of the coronal hole between March 14 and 16, approximately 15° above the boundary. No stream was observed by HELIOS in association with this part of the coronal hole. If the speed was high above the coronal hole, the absence of high speeds at HELIOS implies that the thickness of the northern boundary of the stream was $\lessapprox 15^\circ$ between the sun and 0.3 AU. Assuming a divergence factor of 3 between the corona and a source surface, we infer that the thickness of the northern boundary of this part of the coronal hole was $\leqslant 5^\circ$. This is consistent with our estimates of the thickness of the eastern and western boundaries of the lobe of the coronal hole.

The results presented above lead to the concept that between the sun and ≈ 0.3 AU at least some streams which originate in coronal holes are bounded by a thin shear layer, in which the velocity shear can be as

large as 100 km/sec/degree. The stream boundaries are related to and are a consequence of the coronal hole boundaries. This shear-layer concept is illustrated in Figure 11. It is consistent with the views that recurrent streams originate in coronal holes and that coronal holes have sharp boundaries.

The concept that some streams are bounded by thin shear-layers near the sun conflicts with the published models of recurrent streams. These models assume that near the sun the velocity shear is small, ≈ 3 km/s/degree, in a broad region, whereas the HELIOS observation indicate that the velocity shear is large, ≈ 50 km/s/degree, in a narrow region. Thus, even if the physics of the models is correct, the boundary conditions that have been used may not be appropriate. This is certainly true for the stream A3, and it is probably also true for other streams from coronal holes.

The concept of a narrow shear layer bounding recurrent streams within ≈ 0.3 AU has several dynamical implications. Non-linear effects are important closer to the sun than has been assumed. The magnetic field will be more important in the dynamics, because near the sun the magnetic pressure greatly exceeds the plasma pressure, and signals can be carried much faster by hydromagnetic waves than by sound waves; in other words, stream models must be based on MHD theory rather than on gas dynamic This point was stressed previously by Burlaga et al. (1971) and several MHD models have been constructed (see Hundhausen, 1972). The large velocity shear in the boundary layer might lead to the Kelvin-Helmholtz instability, which would produce MHD waves near the sun (Bavassano et al., 1978; Dobrowolny, 1977; Chandrasekhar, 1961).

V. SUMMARY

HELIOS-1 observed four types of recurrent flows en route to 0.31 AU between December 10, 1974 and March 15, 1975: a broad, recurrent stream of positive polarity; a slow flow ("quiet" wind) of positive and mixed polarity; an evolving slow flow and/or "edge-flow", whose polarity changed from predominantly negative on the first solar rotation to predominantly positive on the third solar rotation; and an evolving compound stream with positive polarity. The streams were related to coronal holes measured in coronal He I 10830Å, and we estimated that the magnetic field intensity in some of these coronal holes was 10 to 20 gauss. Although the streams were recurrent, they were not stationary. They changed in detail from one solar rotation to the next, because the coronal holes which produced them changed in shape and latitude, while their longitude remained nearly constant.

Intense magnetic fields were found in interaction regions, as expected due to kinematic steepening of the streams. Magnetic field enhancements were also found in the form of cold filaments which have not been discussed previously. The field intensity in these CME's (cold, magnetic intensity enhancements) is 2 to 3 times the ambient intensity ahead of them, and the lowest temperature is 0.15 to 0.2 times the ambient temperature. The CME's were observed just ahead of some streams, in the middle of a compound stream, and in some slow flows. The source of the CME's is not understood, but they are probably due to conditions at the sun such as the boundary-zones which surround some coronal holes. CME's which precede streams will influence the dynamics of interaction regions, and thus should be considered in models of streams; the customary

assumption that streams expand into a uniform, "quiet" wind is not always valid.

A narrow recurrent stream was observed at perihelion. This stream was associated with an equatorial extension of a lobe of the south polar hole. The width of the stream was three times the longitudinal width of the coronal hole, consistent with the divergence factors that were derived for flows and fields from coronal holes in other studies. The boundaries of the stream were very thin at 0.3 AU; the width of the forward boundary was 3° and that of the trailing boundary was only 12°. Assuming a divergence factor of three, we infer that the eastern and western boundaries of the stream at the coronal hole were $\approx 2.5^{\circ} \pm 1.5^{\circ}$ wide. We also found that the width of the northern boundary of the stream was $\lesssim 15^{\circ}$ between the sun and 0.3 AU and thus $\lesssim 5^{\circ}$ at the coronal hole. Since the velocities and magnetic fields are nearly radial at $\lesssim$ 0.3 AU, there was a large velocity shear, on the order of 50 km/sec/degree, in the boundary layer surrounding the stream. The thin boundary layer of the stream is a natural consequence of the sharpness of the coronal hole boundary, which presumably marks a transition between open and closed magnetic field lines. Since most coronal holes have sharp boundaries, it is possible that most coronal-hole associated streams are surrounded by thin boundary layers in which there is a large velocity shear. The existing models of streams assume much smaller velocity gradients near the sun. Gas-dynamic models with large velocity gradients would imply the formation of shock pairs near the sun. The formation of shocks would occur at larger distances in a model which considers the effects of the magnetic field and the low density in streams. The magnetoacoustic

speed greatly exceeds the sound speed near the sun, and will cause the pressure pulse to broaden much more rapidly than predicted by a gas-dynamic model. The low density in the streams implies the momentum flux which derives the pressure pulse is smaller than is usually assumed in gas-dynamic models.

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M. Silverstein did most of the programming involved in preparing this paper.

FIGURE CAPTIONS

Figure 1 The top panel shows the solar longitude of HELIOS measured in units of 360^{o} (HSR) with HSR = 0 at the time of launch (December 10, 1974). The bottom panel shows the distance of HELIOS from the sun as a function of time.

Figure 2 The bulk speed and magnetic field polarity (+ fields point away from the sun) as a function of solar longitude for four solar rotations. Four flow patterns are identified by the vertical lines and Roman numerals.

Figure 3 A sketch of the basic flow patterns observed by HELIOS.

Figure 4 Hourly averages of magnetic field intensity measured at HELIOS as a function of solar longitude for four solar rotations. The shaded areas show the locations of interaction regions.

Figure 5 Coronal holes corresponding to the flows in Figure 2.

Figure 6 The longitude (in units of HSR) of the front edges of a stream is plotted versus the Carrington longitude of the front edge of the coronal hole which we associate with that stream. All of the streams in Figure 2 are shown.

Figure 7 A cold magnetic filament (A2a), preceding the interaction region (A2b) of a corotating stream. The essential features of the CMF, are the high-field intensity and the low temperature.

<u>Figure 8</u> A cold magnetic enhancement, which is nearly indistinguishable from an interaction region at the boundary of a stream.

<u>Figure 9</u> Cold magnetic enhancements associated with a compound, recurrent stream.

<u>Figure 10</u> Observations of a coronal-hole associated stream with thin, shear boundaries at 0.3 AU.

<u>Figure 11</u> This illustrates the concept of a shear boundary layer surrounding a coronal-hole associated stream near the sun.

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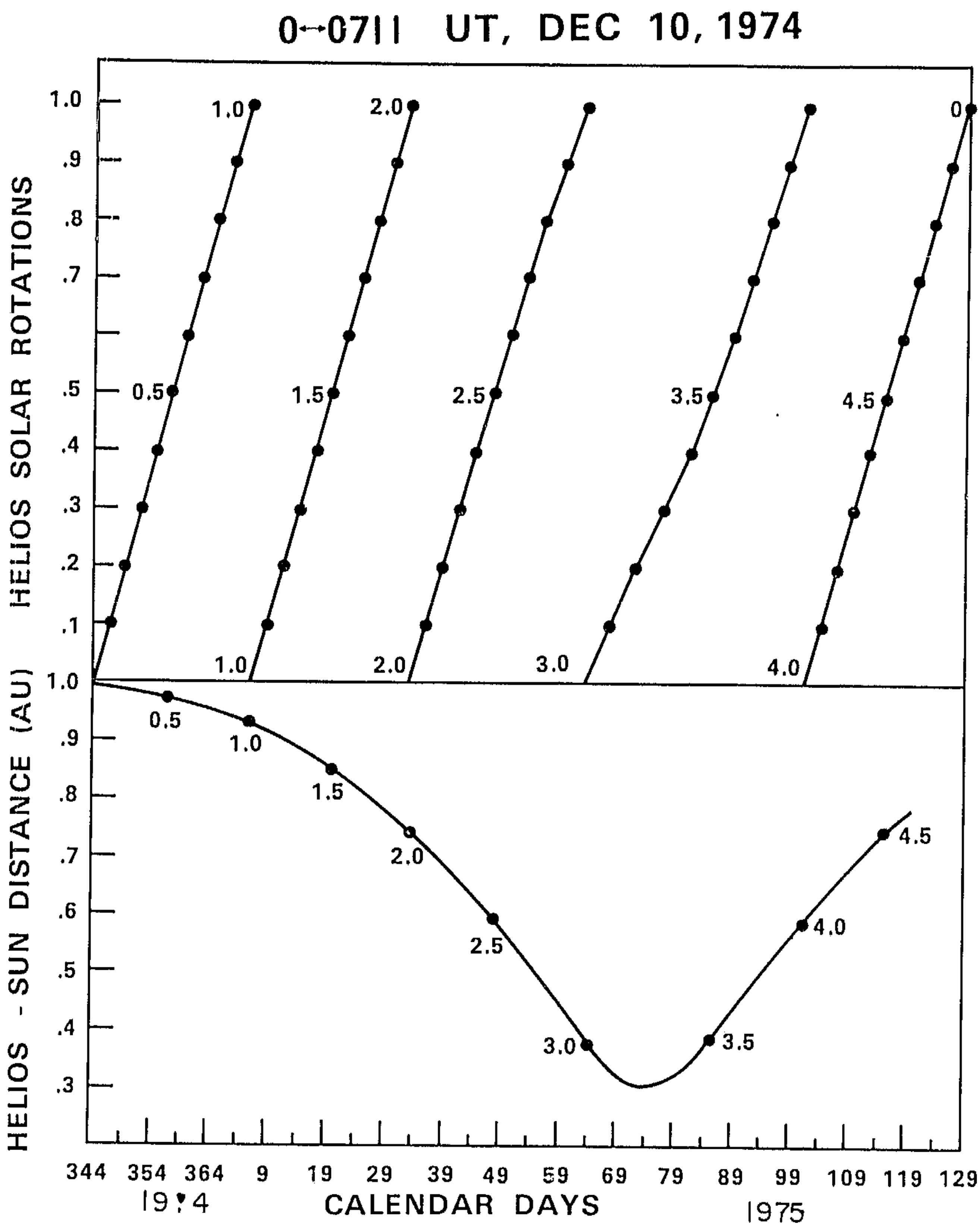
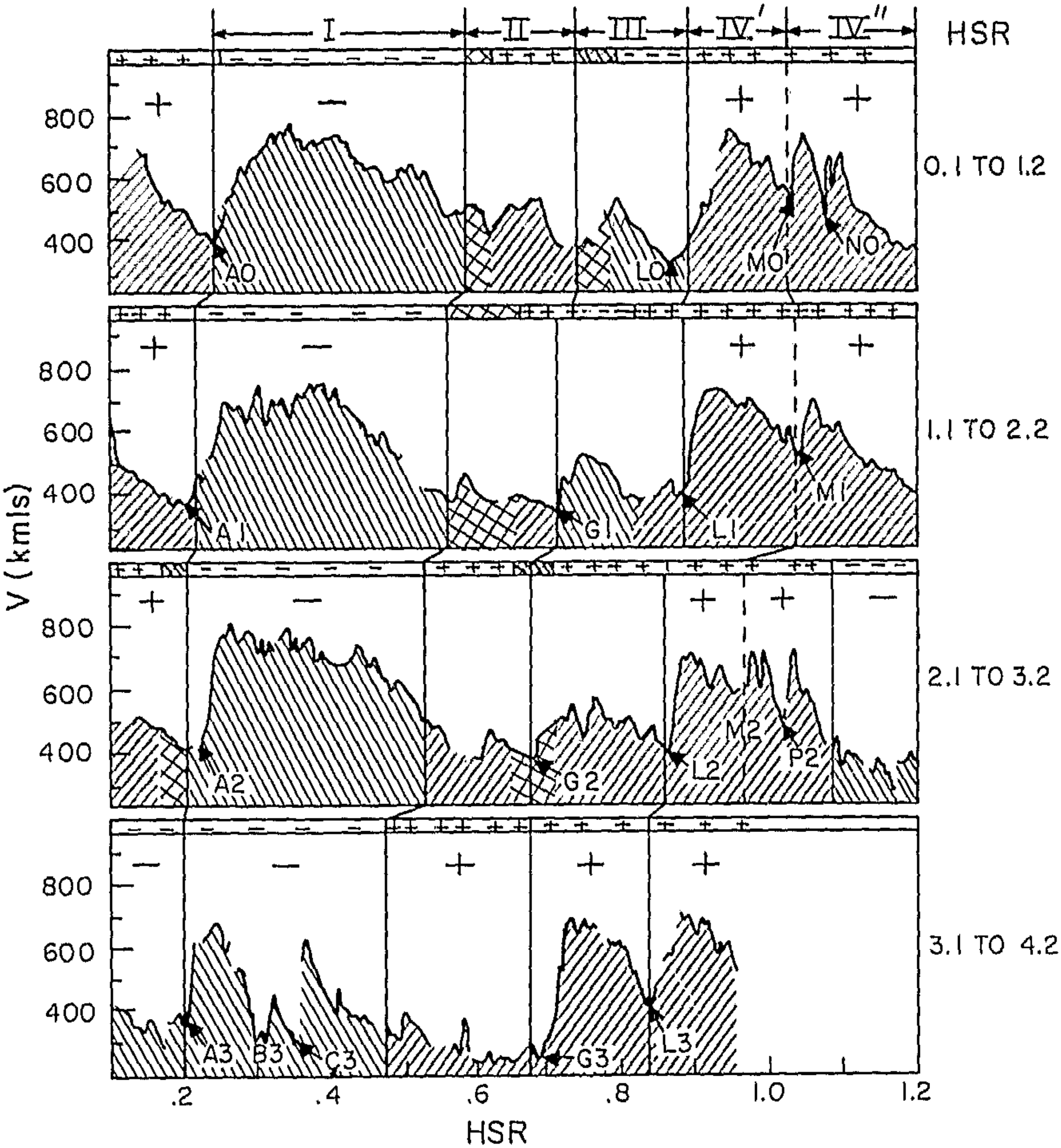


0↔0711 UT, DEC 10, 1974
HELIOS SOLAR ROTATIONS
1.0
.9
.8
.7
.5
.4
.3
.2
.1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0
HELIOS - SUN DISTANCE (AU)
1.0
.9
.8
.7
.6
.5
.4
.3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
344 354 364 9 19 29 39 49 59 69 79 89 99 109 119 129
1974
CALENDAR DAYS
1975

Figure 1



I
II
III
IV′
IV″
HSR
V (km/s)
800
600
400
0.1 TO 1.2
1.1 TO 2.2
2.1 TO 3.2
3.1 TO 4.2
A0
L0
M0
N0
A1
G1
L1
M1
A2
G2
L2
M2
P2
A3
B3
C3
G3
L3
.2
.4
.6
.8
1.0
1.2
HSR

Figure 2

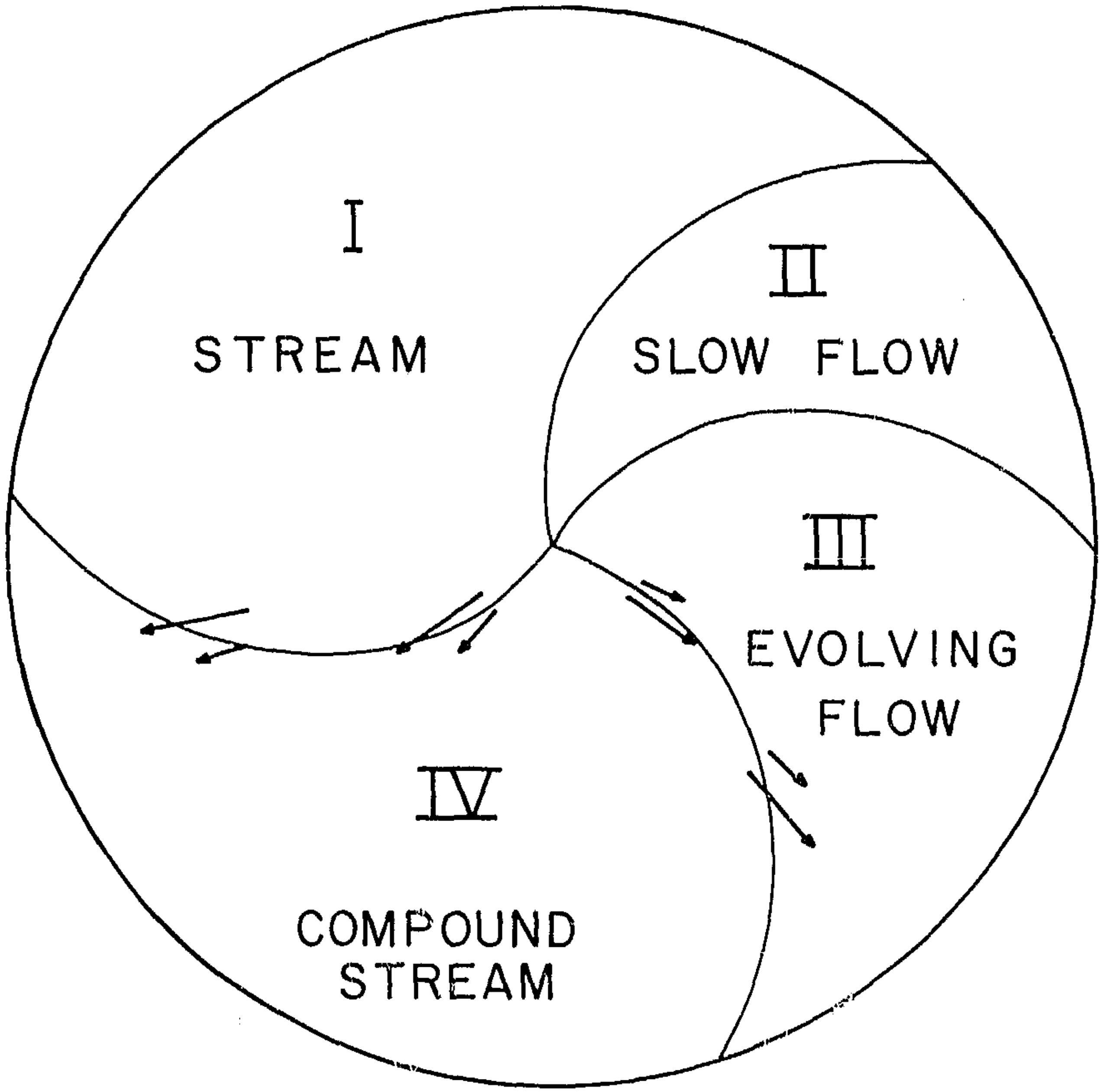


Figure 3

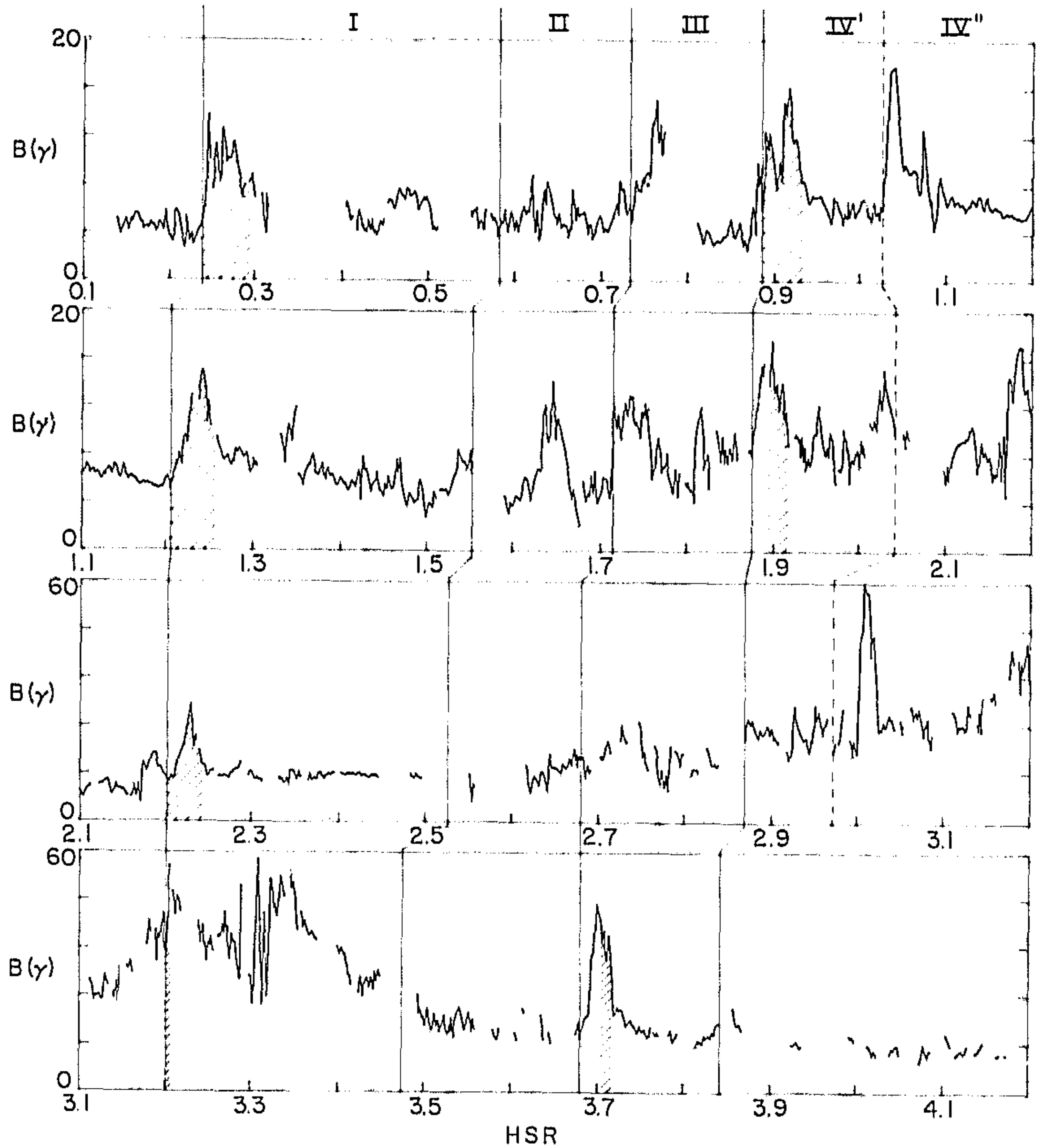

I
II
III
IV'
IV''
B(γ)
20
0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
60
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
HSR

Figure 4

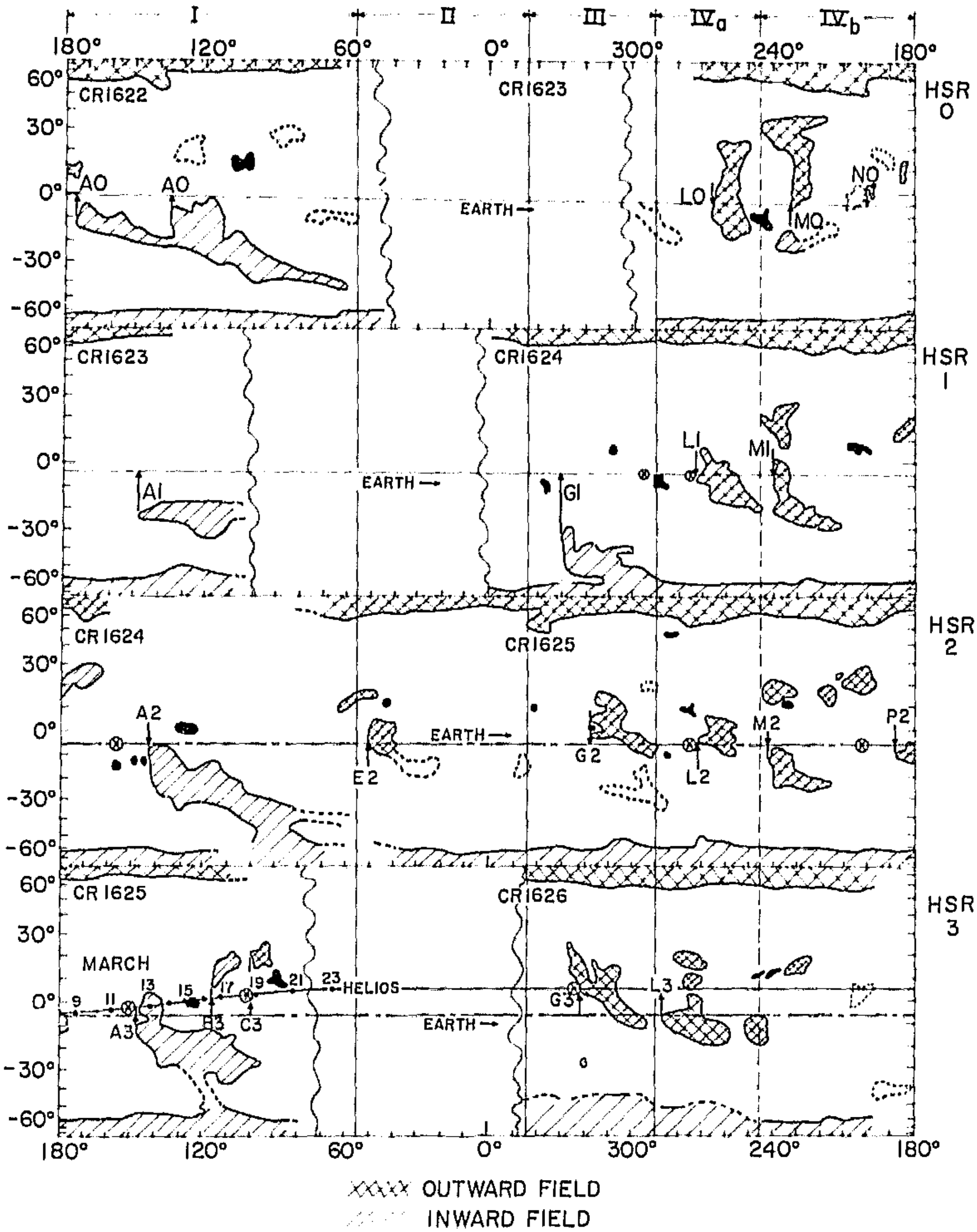
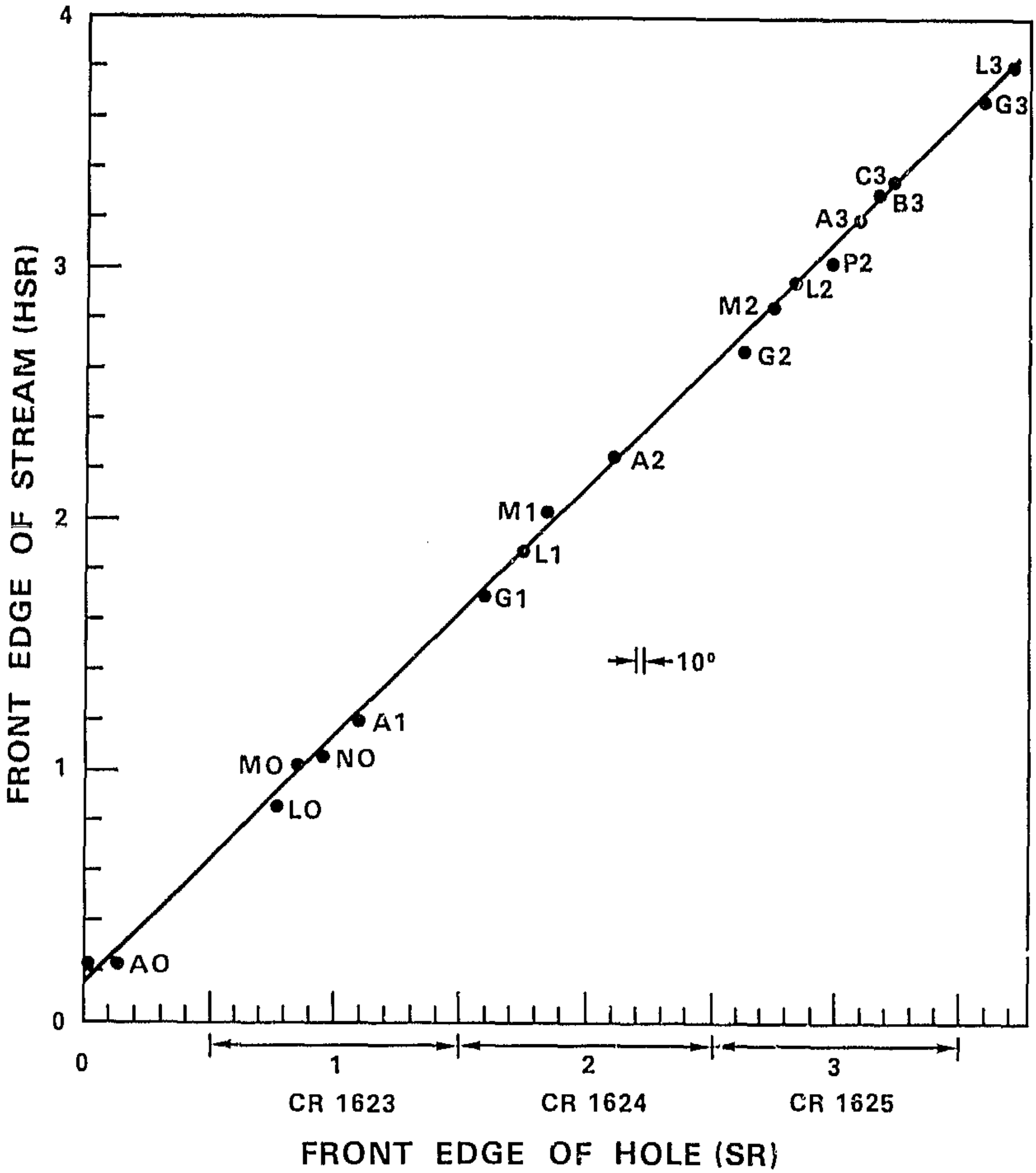


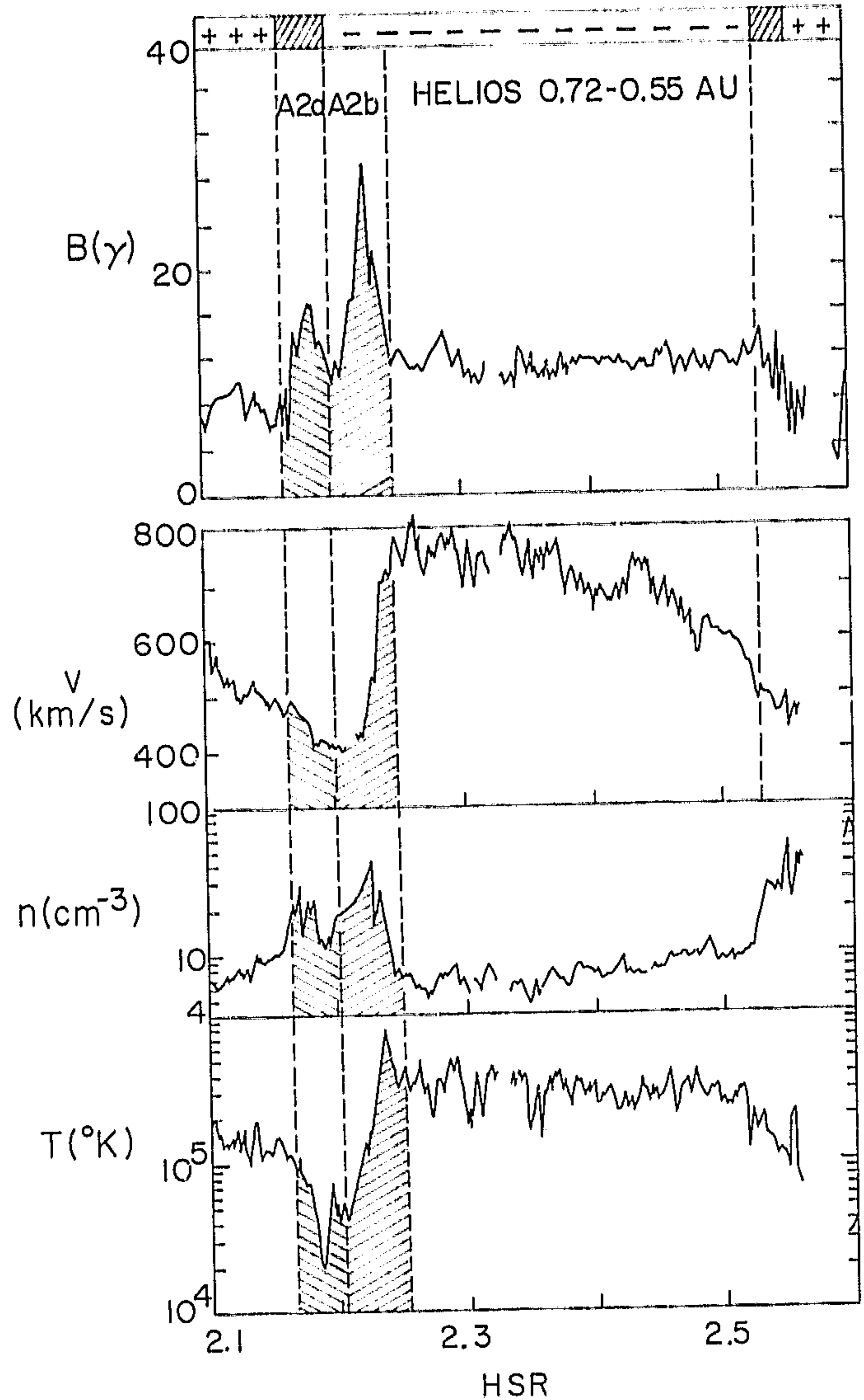
Figure 5

ORIGINAL PAGE IS
OF POOR QUALITY



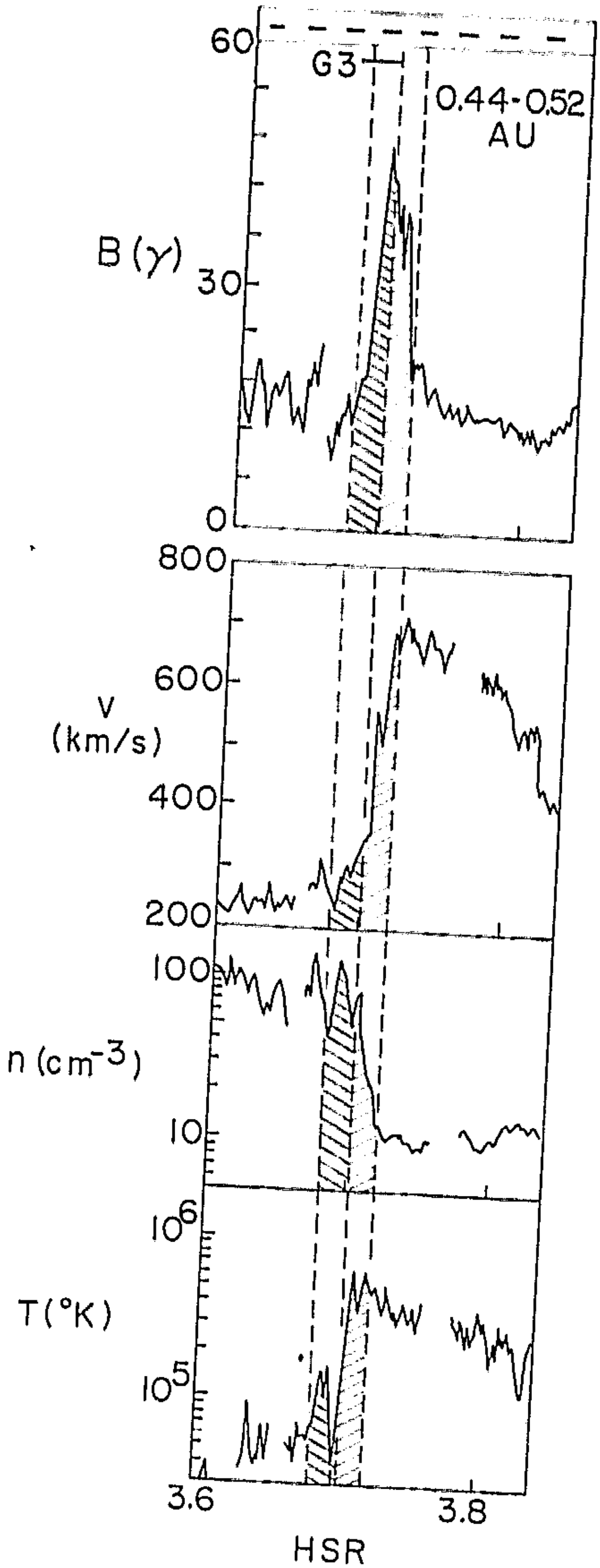
FRONT EDGE OF STREAM (HSR)
4
3
2
1
0
L3
G3
C3
B3
A3
P2
L2
M2
G2
A2
M1
L1
G1
10°
A1
MO
NO
LO
AO
0
1
2
3
CR 1623
CR 1624
CR 1625
FRONT EDGE OF HOLE (SR)

Figure 6



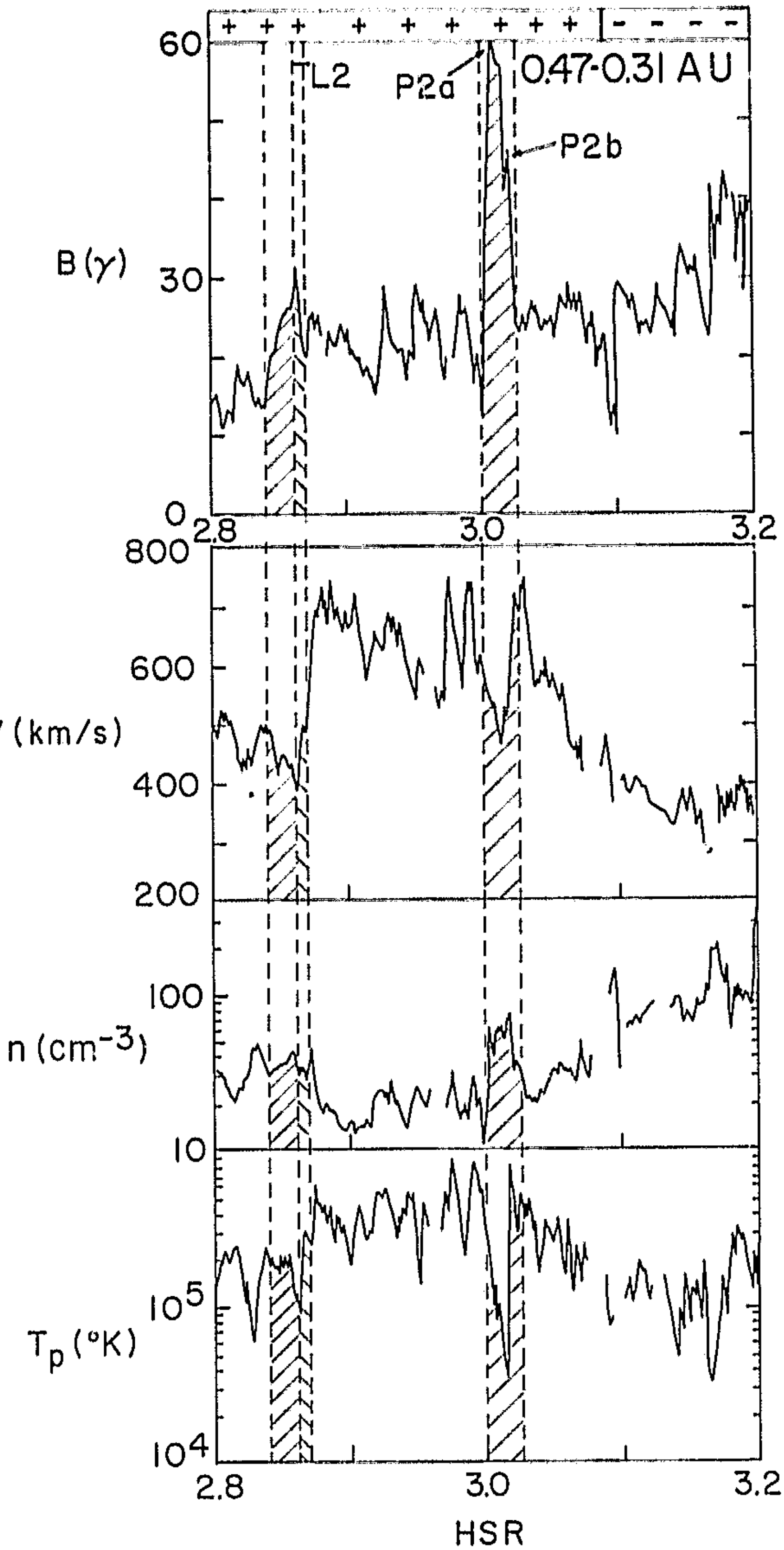
+ + +
− − − − − − − − − − − −
+ +
A2d
A2b
HELIOS 0.72-0.55 AU
B(γ)
40
20
0
800
600
400
V
(km/s)
100
10
4
n(cm^-3)
T(°K)
10^5
10^4
2.1
2.3
2.5
HSR

Figure 7



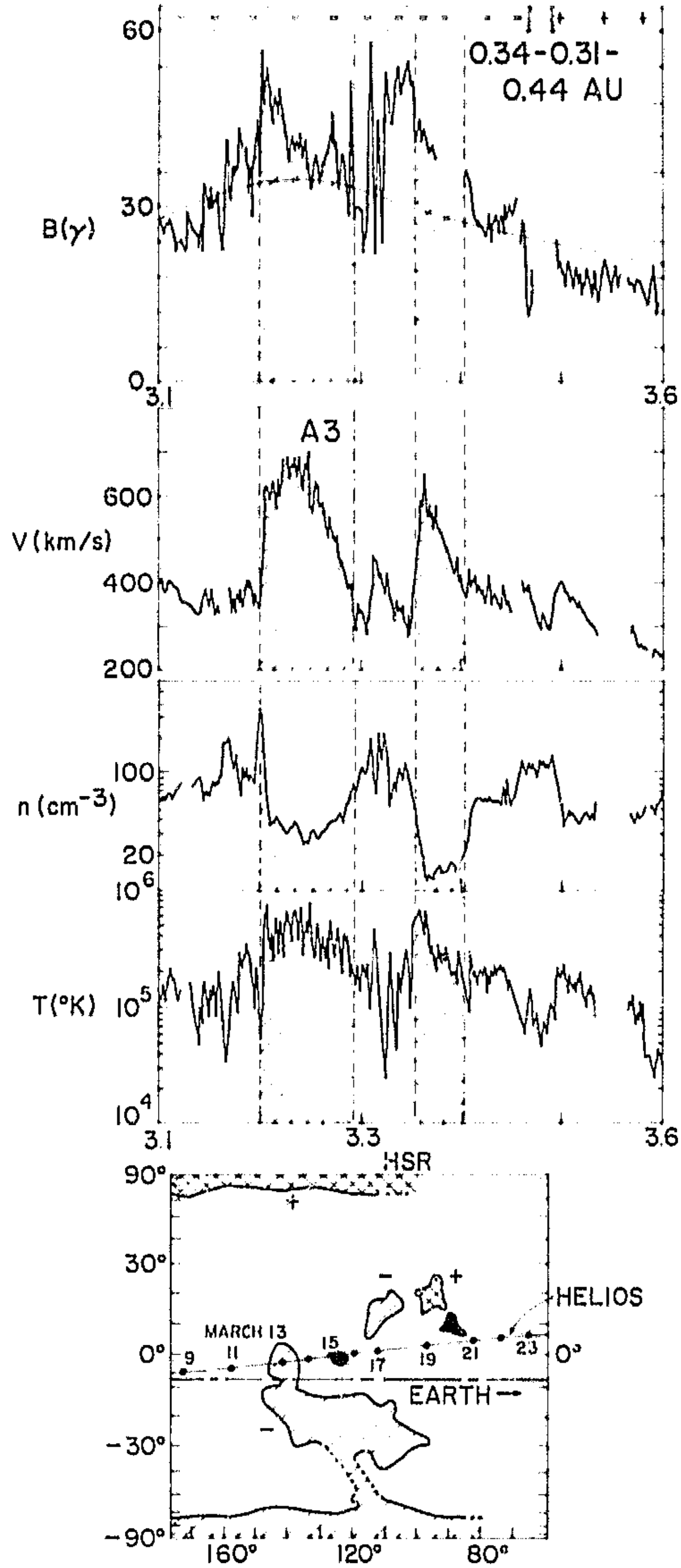
60
G3
0.44-0.52
AU
B (γ)
30
0
800
600
v
(km/s)
400
200
100
n (cm⁻³)
10
10⁶
T(°K)
10⁵
3.6
3.8
HSR

Figure 8



+ + + + + + + + + - - - -
TL2
P2a
0.47-0.31 AU
P2b
B (γ)
60
30
0
2.8
3.0
3.2
800
600
V (km/s)
400
200
100
n (cm⁻³)
10
Tp (°K)
10⁵
10⁴
2.8
3.0
3.2
HSR

Figure 9



0.34-0.31-
0.44 AU
B(γ)
60
30
0
3.1
3.6
A3
V (km/s)
600
400
200
n (cm-3)
100
20
T(°K)
10^6
10^5
10^4
3.1
3.3
3.6
HSR
90°
30°
0°
-30°
-90°
HELIOS
MARCH 13
9
11
15
17
19
21
23
EARTH
160°
120°
80°

Figure 10

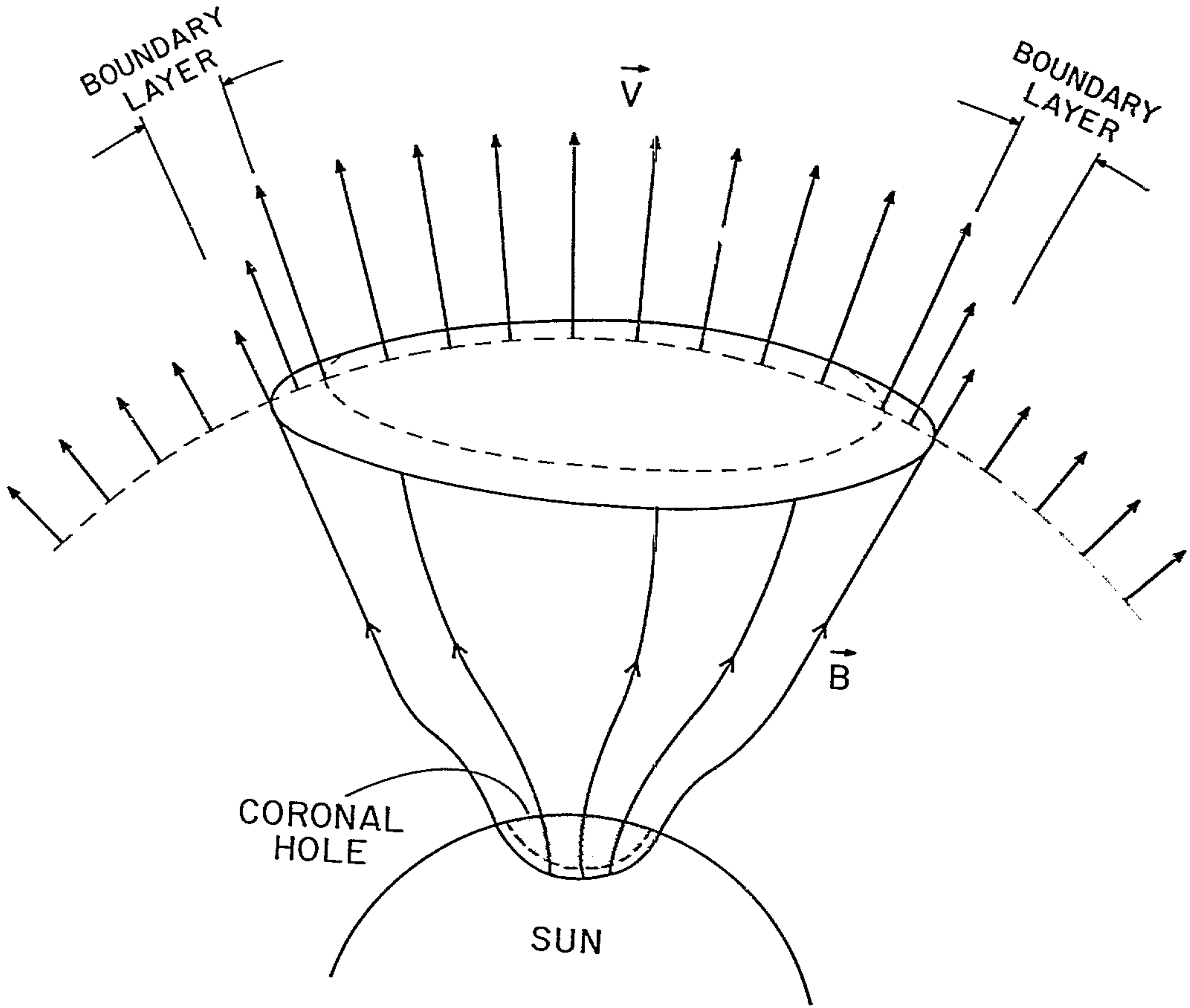


Figure 11

BIBLIOGRAPHIC DATA SHEET

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16. Abstract

HELIOS-1 moved from 1 AU on December 10, 1974, to 0.31 AU on March 15, 1975, and the sun rotated beneath the spacecraft nearly four times during the interval. Recurrent high-speed streams with uniform magnetic polarity were observed, and they were associated with coronal holes of the same polarity. Although recurrent, the streams and their magnetic field patterns were not stationary, because the coronal holes which produced them changed in shape and latitude from one rotation to the next. We estimated that the magnetic field intensity of open field lines in some of these holes was on the order of 10 to 20 gauss. Recurrent slow flows were also observed. The magnetic field polarity and intensity in these flows were irregular and they changed from one rotation to the next.

Cold magnetic enhancements (CME's) characterized by a 2 to 3 fold enhancement of magnetic field intensity and a 5 to 7 fold depression of proton temperature relative to conditions ahead of the CME's, were observed in some slow flows. Some of these CME's were contiguous with interaction regions of streams.

At perihelion, HELIOS observed a recurrent stream which was associated with a lobe of the south polar coronal hole. The longitudinal width of the stream was three times that of the hole. We estimate that the width of the

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eastern and western boundaries of the streams at the coronal holes was only $2.5^{\circ} \pm 1.5^{\circ}$, and we infer that the width at the northern boundary of the stream was $\lesssim 5^{\circ}$. We conclude that between the sun and 0.3 AU there was a diverging stream surrounded by a thin boundary layer in which there was a large velocity shear. There is evidence for compression of the magnetic field in the western boundary layer (interaction region), presumably due to steepening of the stream within 0.31 AU. The magnetic field must be considered in models of the boundary layer and the stream.